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EFFECT OF CELL STATE-OF-CHARGE ON OUTCOME OF INTERNAL CELL FAULTS: PRELIMINARY REPORT

(BY: E^X^PONENT FAILURE ANALYSIS ASSOCIATES)

Exponent®

Failure Analysis Associates®

Effect of Cell State-of-Charge on Outcome of Internal Cell Faults: Preliminary Report

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Purpose of Testing

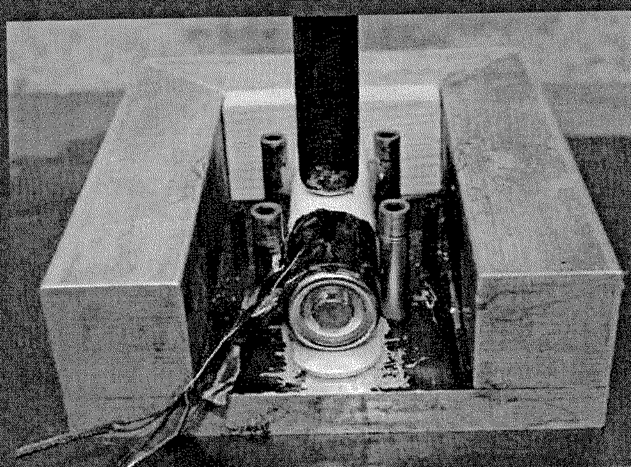
- Examine the effect of cell state-of-charge (SOC) on the outcome of a low impedance internal cell fault
- SOC is the charge level of a battery cell divided by its charge capacity
  - The higher the SOC, the more energy available for release by an internal cell fault for comparable capacity cells. Higher energy release increases the probability of severe outcomes:
    - Fire
    - Energetic disassembly
  - For a given cell, the nature of the internal cell fault will determine the initial rate of energy release and potentially the severity of outcome

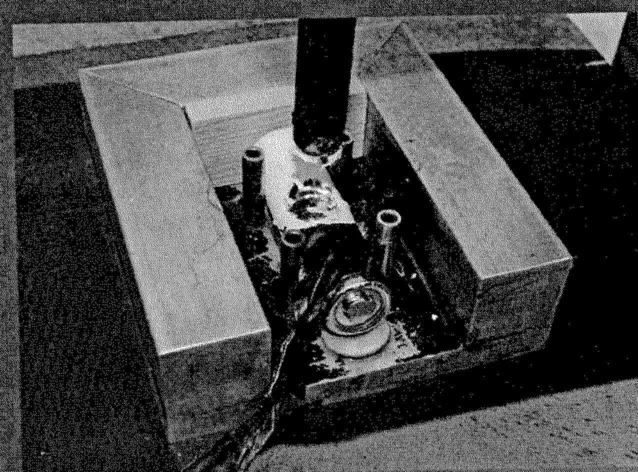
Purpose of Testing (cont)

- An internal cell fault could result from several causes, including:
  - Mechanical damage
  - External overheating
  - Overcharging or other charging anomalies
  - Charge cycling a cell with a manufacturing defect

General Test Methodology

- Induce low impedance internal cell fault in controlled and repeatable manner
  - Crush cell with arbor press*
    - Cell crush represents severe abuse conditions resulting in
      - Multiple low impedance shorts
      - Potential for rapid energy release
    - Provides a method to explore cell behavior during high discharge rate internal cell faults

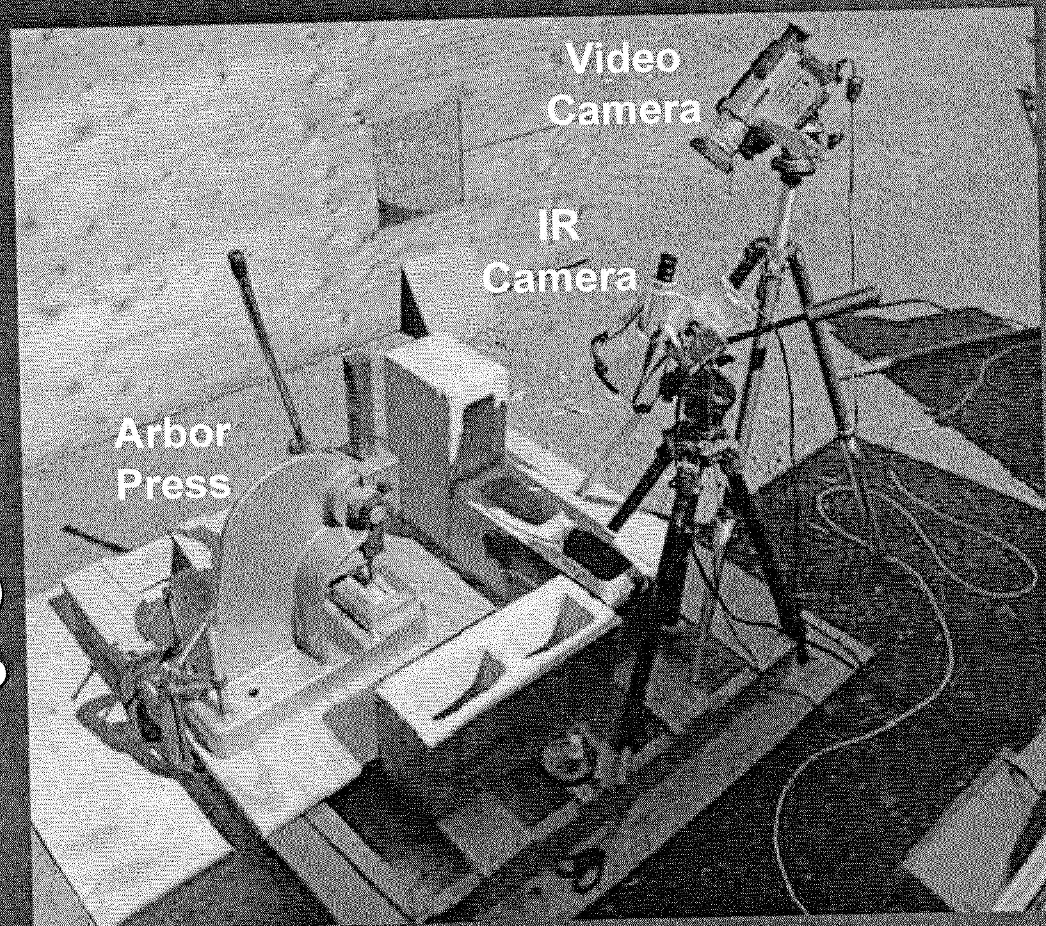




* General approach described in IEEE 17th Annual Battery Conference on Applications and Advances paper "On the Testing Method of Simulating a Cell Internal Short Circuit for Lithium Ion Batteries" by J.Loud, S.Nilsson, and Y.Du, Long Beach 2002.

Test Setup and Instrumentation

- Cell temperature measurements
  - Thermocouples on cell surface near crush zone
  - Infrared (IR) camera measures cell temperatures (surface painted white to allow accurate readings)
- IR data correlates to localized thermocouple measurements



Crush Profile

- To initiate a severe internal cell fault
  - Crush must be aggressive enough to create low impedance shorting within cell
    - Goal is to induce an “internal short” condition leading to thermal runaway
      - Cell heating (temperature rises to >100 °C)
      - Rise in internal pressure
  - Crush must not be so aggressive that it cracks the cell case
    - A case crack would act as a secondary cell vent
    - A case crack would reduce severity of outcome
    - Tests where the case cracks during crushing should not be directly compared to tests where case integrity has been maintained

Crush Profile

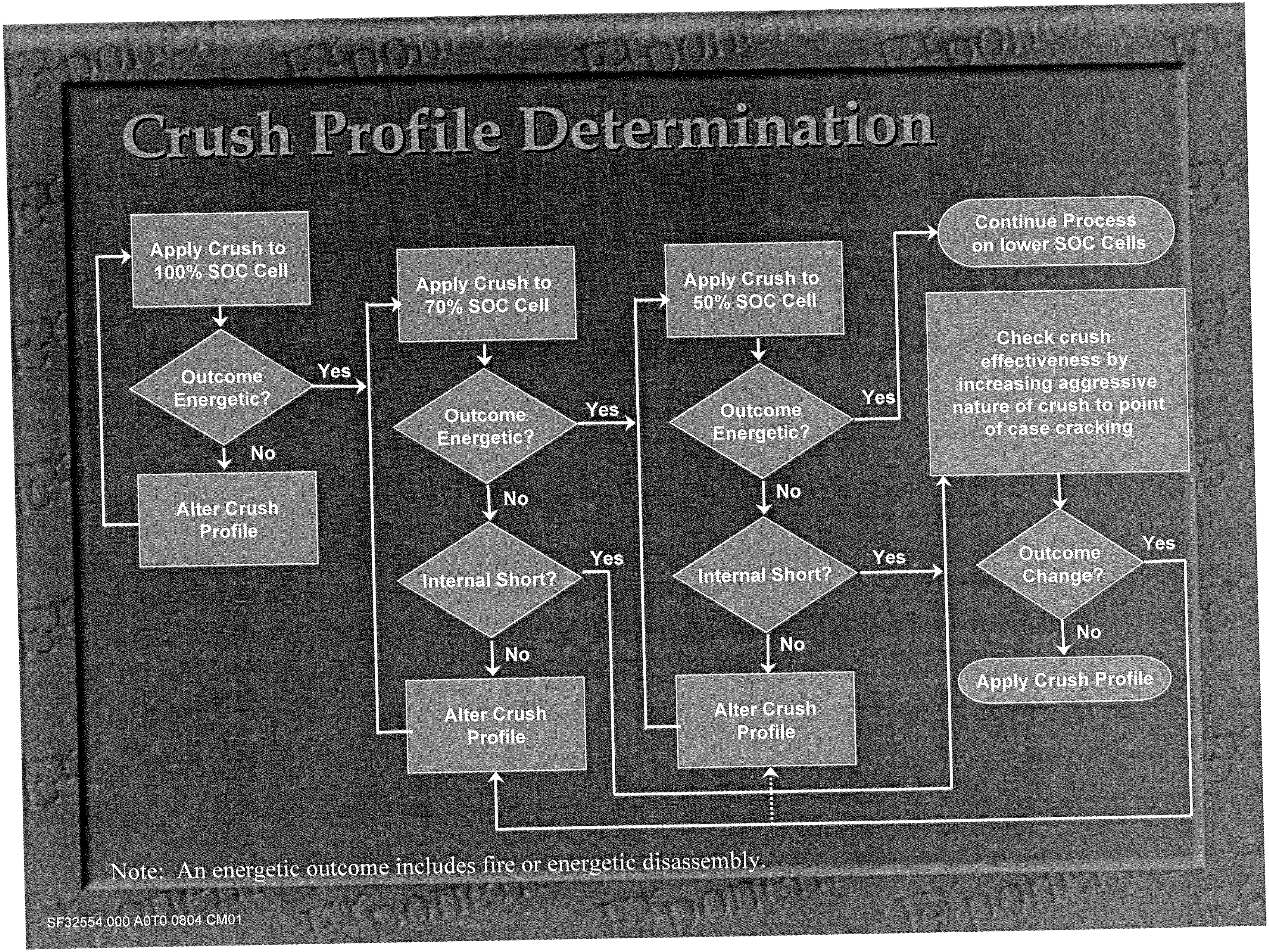
- Cell designs vary between manufacturers and brands
  - Thickness of case wall
  - Ductility of case material
  - Rigidity of cell windings ("jelly roll")
- Preliminary testing showed
  - Any single crush profile (force or depth) has limitations
    - Might induce low impedance shorts in cells by some manufacturers, while not inducing them in others.
    - Might induce low impedance shorts in all cells, but also cause case cracks with a particular cell design

Crush Profile

- Preliminary testing showed
  - Crush profile can be tailored on a per brand or manufacturer basis to induce internal short by causing low impedance shorting with cracking the case
    - Increase crush aggressiveness until internal short achieved
    - Stop just short of causing case cracking
    - If internal short not achievable without also causing case cracking, try a multi-pulse crush

Crush Profile

- Crush tests that consistently achieve a low impedance cell fault have the following advantages
  - Allow direct comparison of different test cell brands or manufacturers
  - Allow for varying states-of-charge and difference capacities
  - Allow for estimating the performance of other lithium-ion cells with similar energy densities and technologies


Crush Profile Determination
Apply Crush to 100% SOC Cell
Outcome Energetic?
Yes
No
Alter Crush Profile
Apply Crush to 70% SOC Cell
Outcome Energetic?
Yes
No
Internal Short?
Yes
No
Alter Crush Profile
Apply Crush to 50% SOC Cell
Outcome Energetic?
Yes
No
Internal Short?
Yes
No
Alter Crush Profile
Continue Process on lower SOC Cells
Check crush effectiveness by increasing aggressive nature of crush to point of case cracking
Outcome Change?
Yes
No
Apply Crush Profile
Note: An energetic outcome includes fire or energetic disassembly.
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Cells Used in Testing

- State of the art (at the time of testing) 18650 style cells were obtained from three manufacturers
- 5 Cells per manufacturer were measured to verify cell capacity

Manufacturer Identification Color Code	Nominal Rated Capacity	Measured Capacity
A (Orange)	2.10 Ah	2.16 Ah ± 1.5%
B (Green)	2.20 Ah	2.16 Ah ± 2.0%
C (Blue)	2.15 Ah	2.15 Ah ± 1.5%

Manufacturer Cell Capacity Evaluation

- Capacity variation determined before discharging to selected SOC
  - 5 cells per manufacturer were charged to 4.2 V and discharged through a calibrated resistor to 3.0 V while recording voltage, current, temperature, and time
    - Nominal capacities were within 3% of manufacturer specifications
    - Cell-to-cell capacity within brand varied 3-4%
- The SOC was set by discharging at 0.75 C
  - The 0.75 C rate was calculated using the specified cell capacities
  - 1 C is the constant discharge current that drains the nominal cell capacity in 60 min.
  - 0.75 C drains a fully charged cell in 80 min.

Setting SOC

- Nominal capacities for the three manufacturers are 2.10, 2.15, and 2.20 Ah
- Charging to 4.2 V (100% SOC)
- Discharging from 100% SOC with a constant 0.75 C across a dynamic load for a pre-determined period of time to reach lower SOCs

SOC [%]	Discharge time [min]
100 → 100	0
100 → 70	24.0
100 → 50	40.0
100 → 40	48.0
100 → 30	56.0

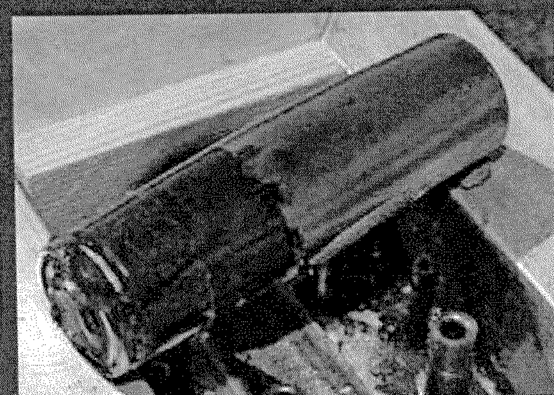
Observed Crush Outcomes

- Observed crush outcomes have been classified into four categories, listed in decreasing order of severity
  - Fire: a "Severe" outcome
  - Energetic Disassembly: a "Severe" outcome
  - Case Rupture: a "Moderate" outcome
  - Internal short: a "Minimum" outcome
- Characterization is based on the most severe result observed:
  - Though an internal short condition was induced in all cells, a particular test was labeled "internal short" only when it did not exhibit any of the other outcomes.
  - Though the incidence of fire is sometimes accompanied by an energetic disassembly, all tests that resulted in fire were included only in the "Fire" category

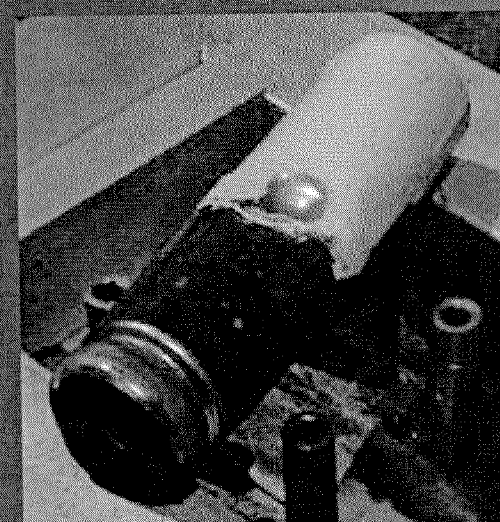
Fire Outcome

- Coincident with crush action
  - Appearance of flames
  - "Pop" or "hissing" sound
  - Cell may or may not disassemble or rupture
  - Rapid temperature rise immediately upon crush, on the order of 100 °C per second

Fire with Case Rupture

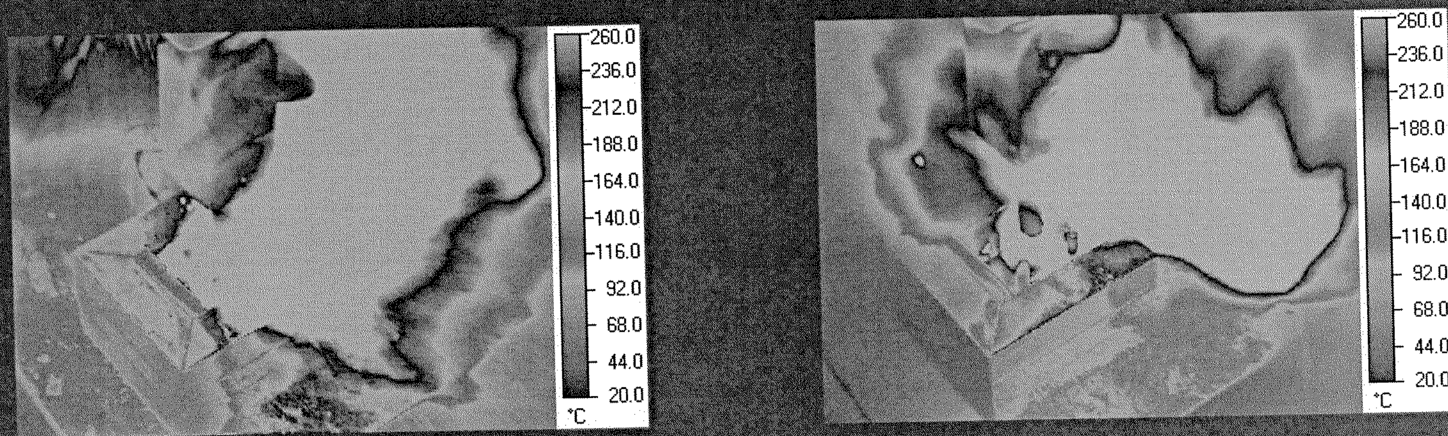


Fire with Cell Venting

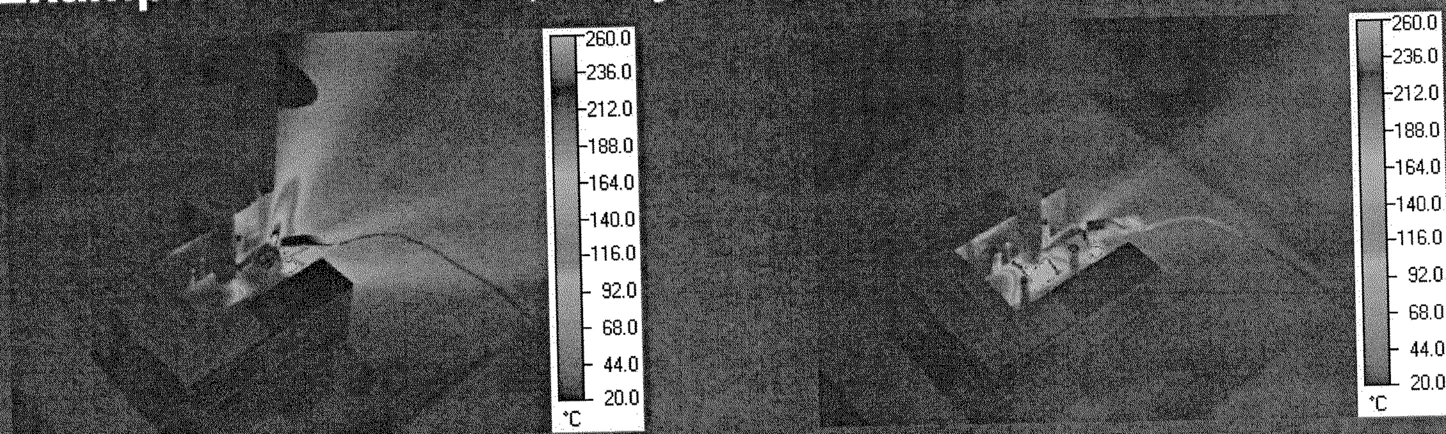


Fire with Energetic Disassembly

Fire Outcome

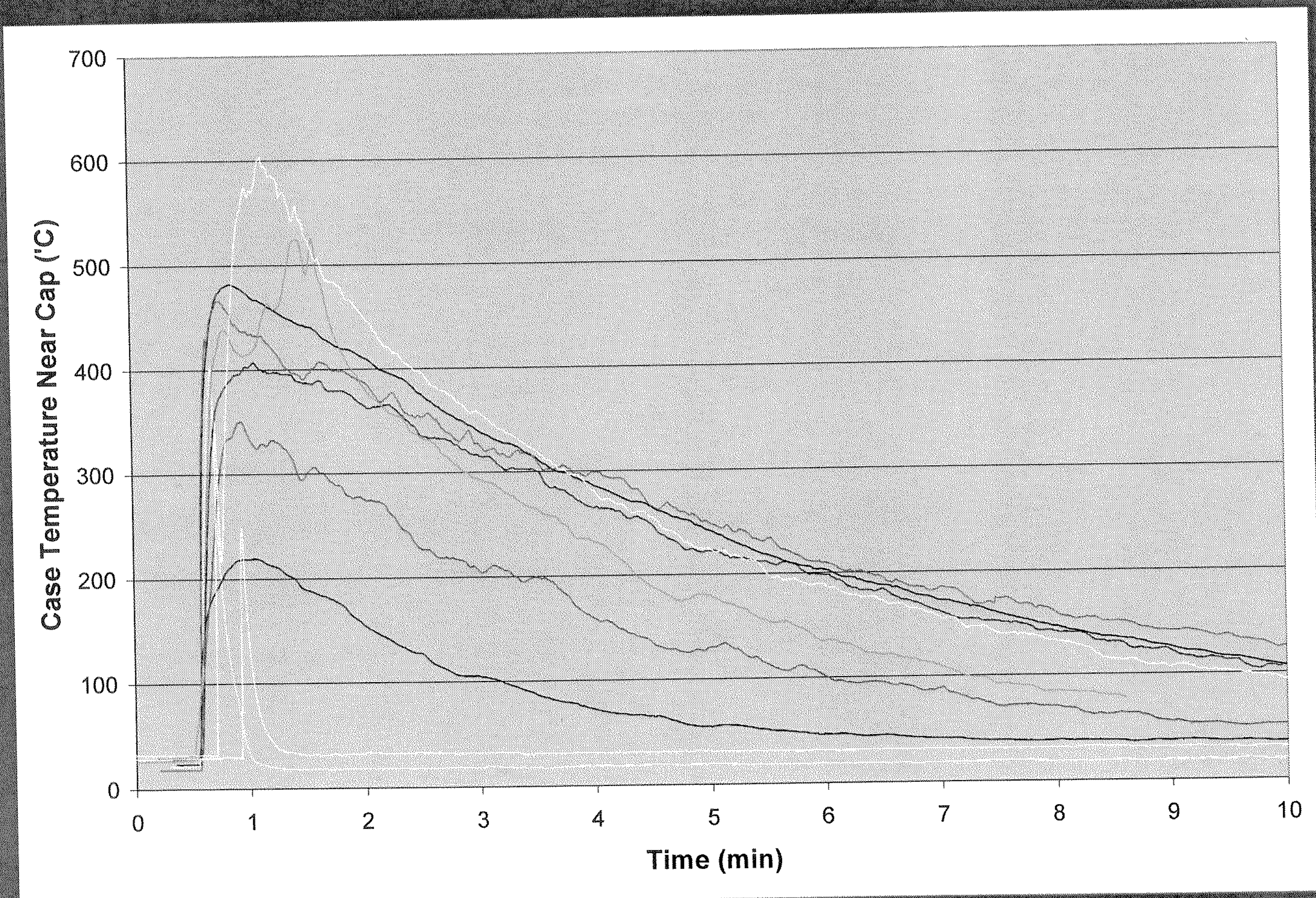


Example 1: 70% SOC, early stage (left), later stage (right)



Example 2: 70% SOC, early stage (left), later stage (right)

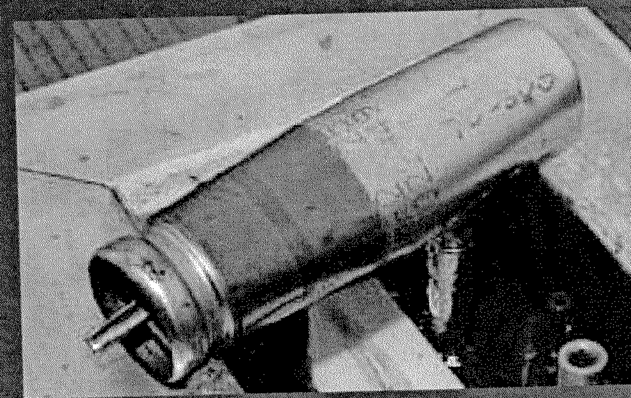
Fire Outcome

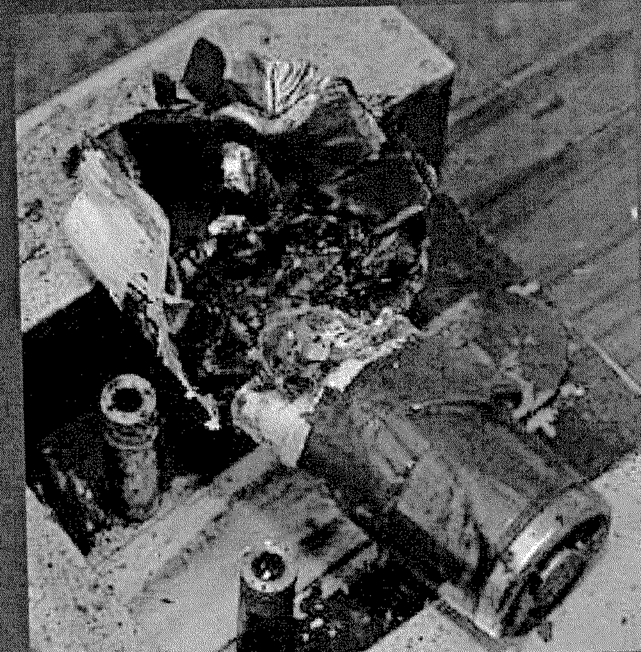


Thermocouple Data for nine 70% SOC cells

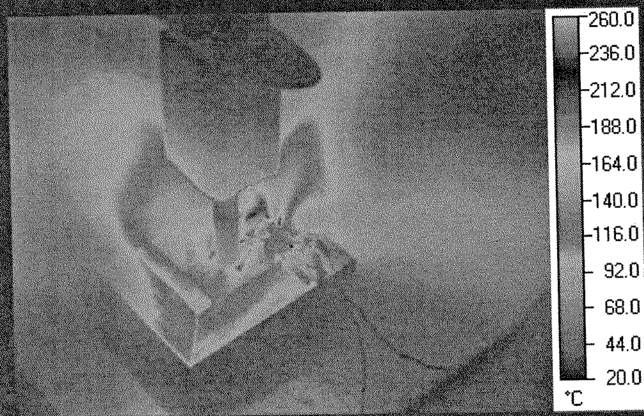
Energetic Disassembly Outcome

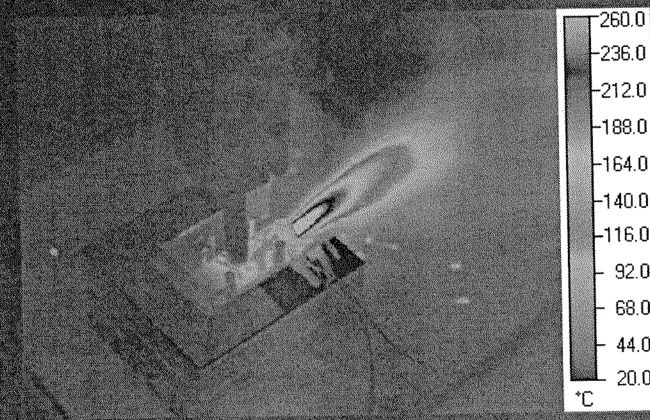
- Coincident with crush:
  - Loud "Pop" sound
  - Cell cap may be projected
  - Significant portion (~ 1/3 to 1/2) of jellyroll may be ejected
  - Local temperature rise similar to fire outcome for a short period
  - Temperature rise of remaining jellyroll similar to internal short





Energetic Disassembly Outcome

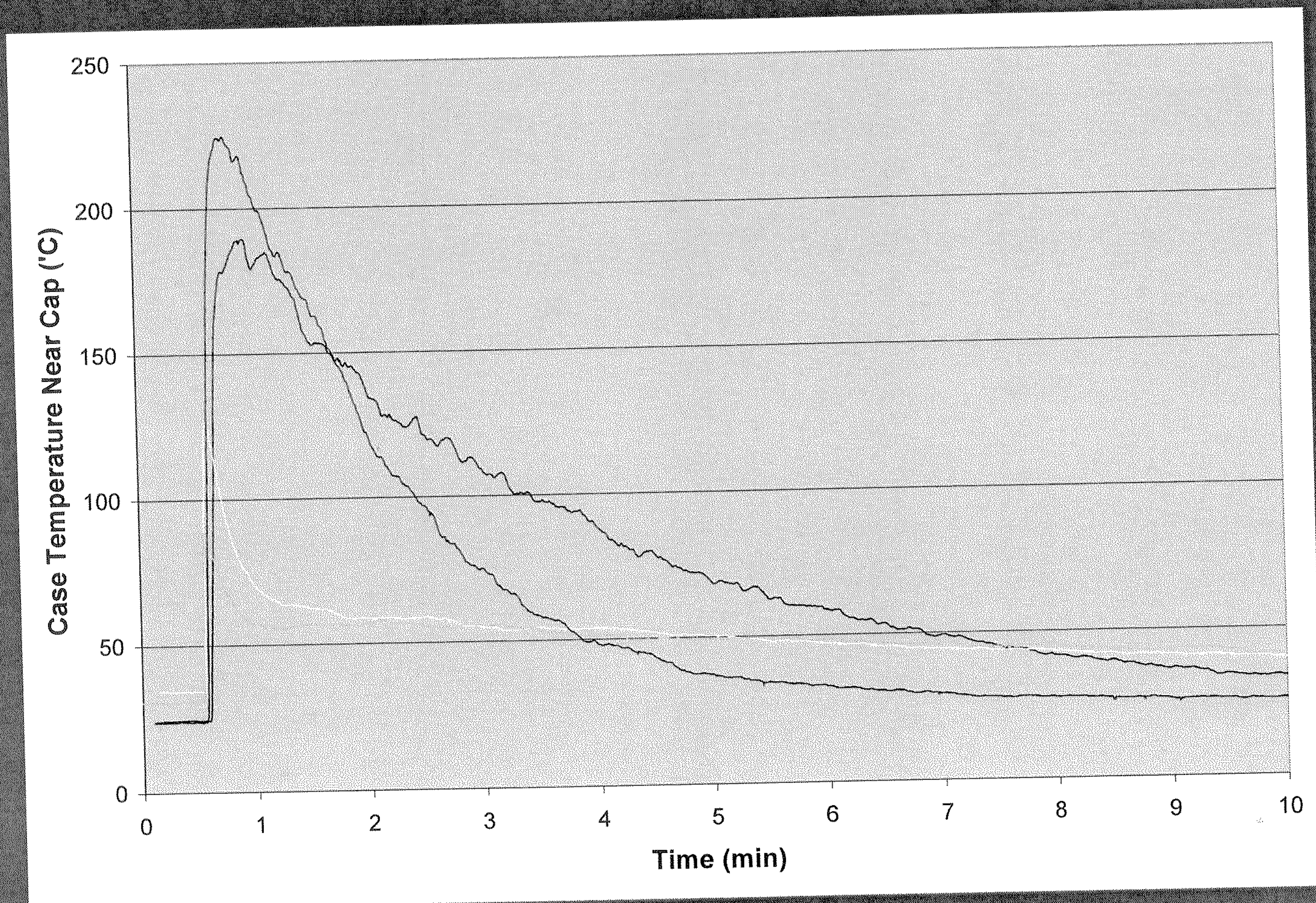




Example 1: 70% SOC, initial stage (left), ejection (right)

Example 2: 70% SOC, ejection (left), later stage (right)

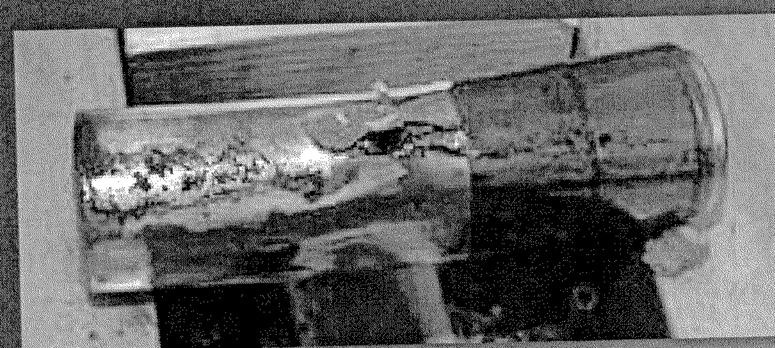
Energetic Disassembly Outcome



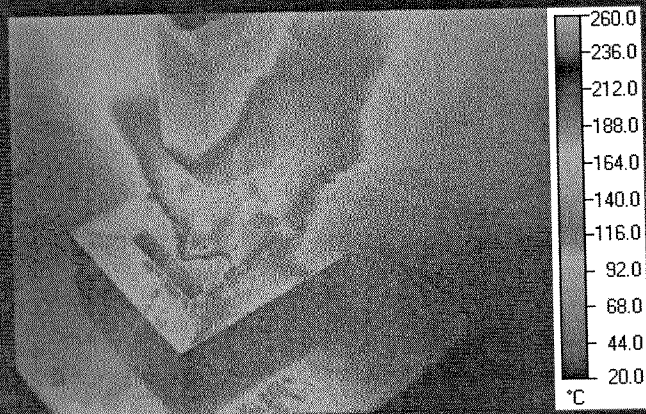
Thermocouple Data for three 70% SOC & one 100% SOC cells

Case Rupture Outcome

- Coincident with crush:
  - Loud "Pop" sound
  - Brief release of hot gases
  - Case ruptures along the side (fish-mouth opening created)
    - Bulk of jellyroll remains in place
    - Portions of exposed jellyroll windings expelled
    - Cap remains in place, vent activates
  - Case temperature maximum and rise rate similar to internal short outcome
- Case ruptures caused by overpressure during the internal short



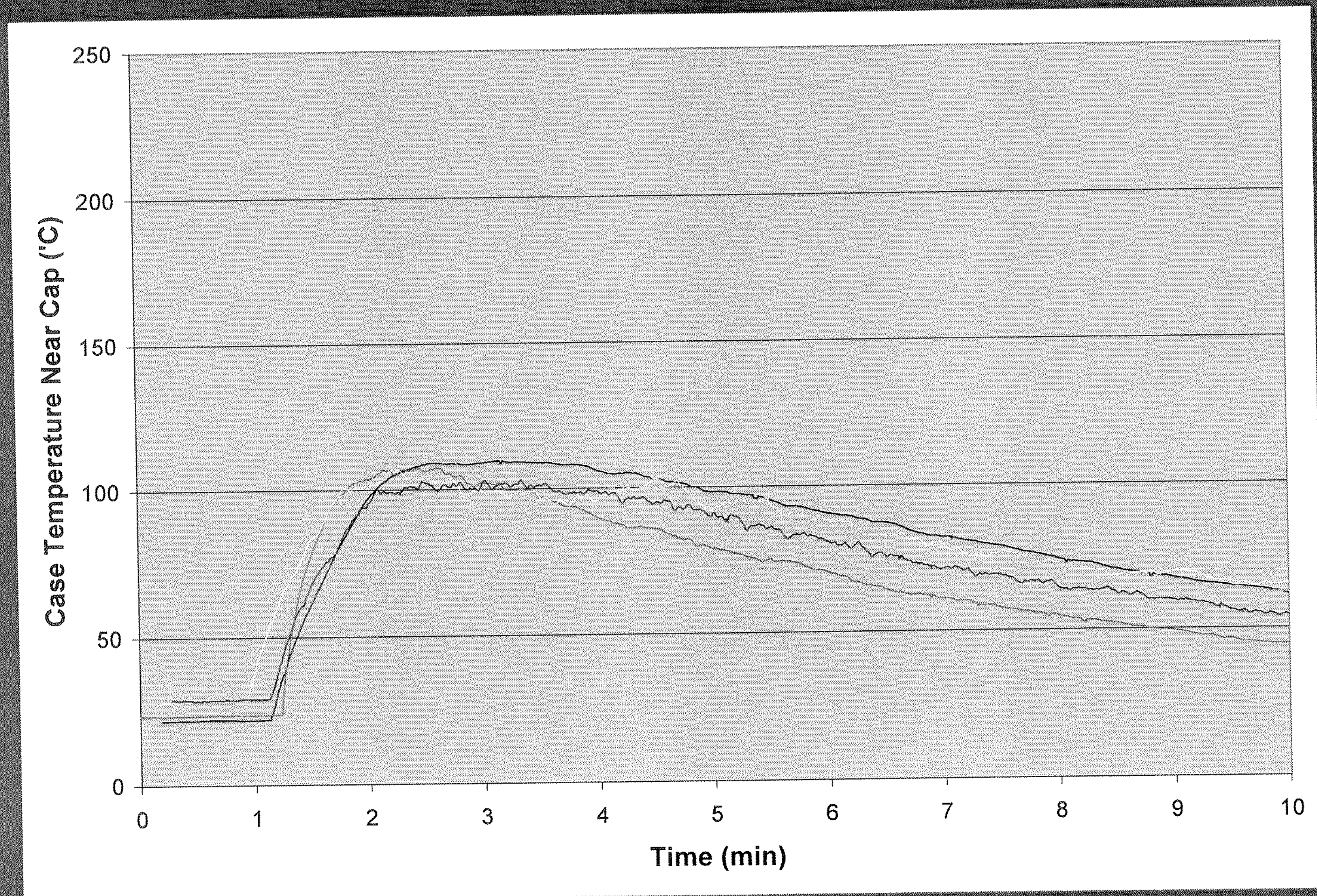
Case Rupture Outcome



Example 1: 70% SOC, early stage (left), later stage (right)

Example 2: 50% SOC, early stage (left), later stage (right)

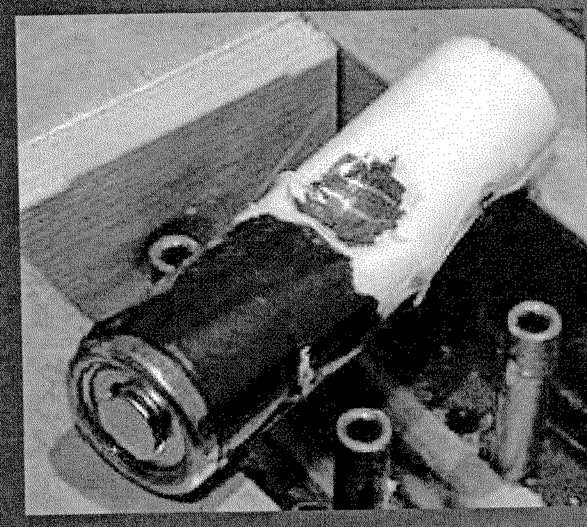
Case Rupture Outcome



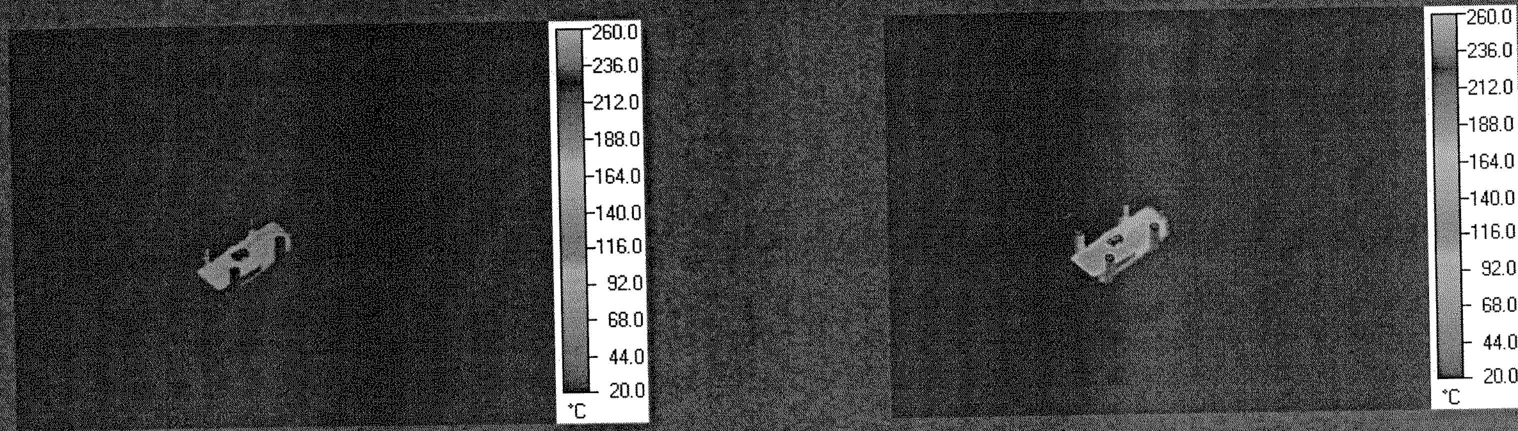
Thermocouple Data for one 50% SOC & four 70% SOC cells

Internal Short Outcome

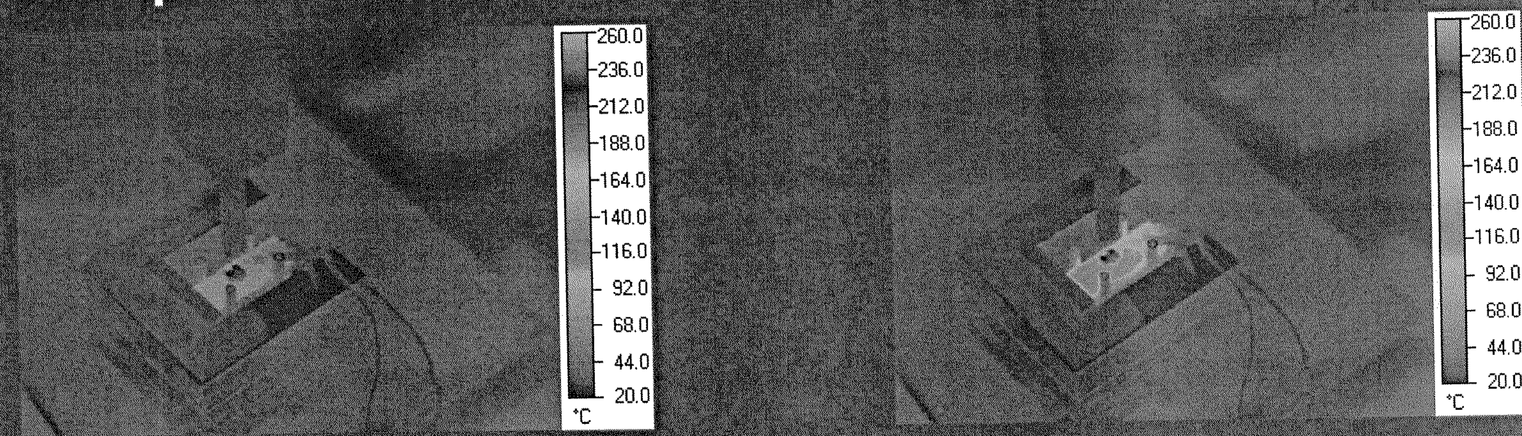
- Coincident with crush:
  - Soft or inaudible "pop" sound (vents activating)
  - Some designs contain up to three stages of vents
- After crush
  - Cell heating
    - To >100 °C, at a rate of approximately 70 °C/min
  - Electrolyte can be released through vent



Internal Short Outcome

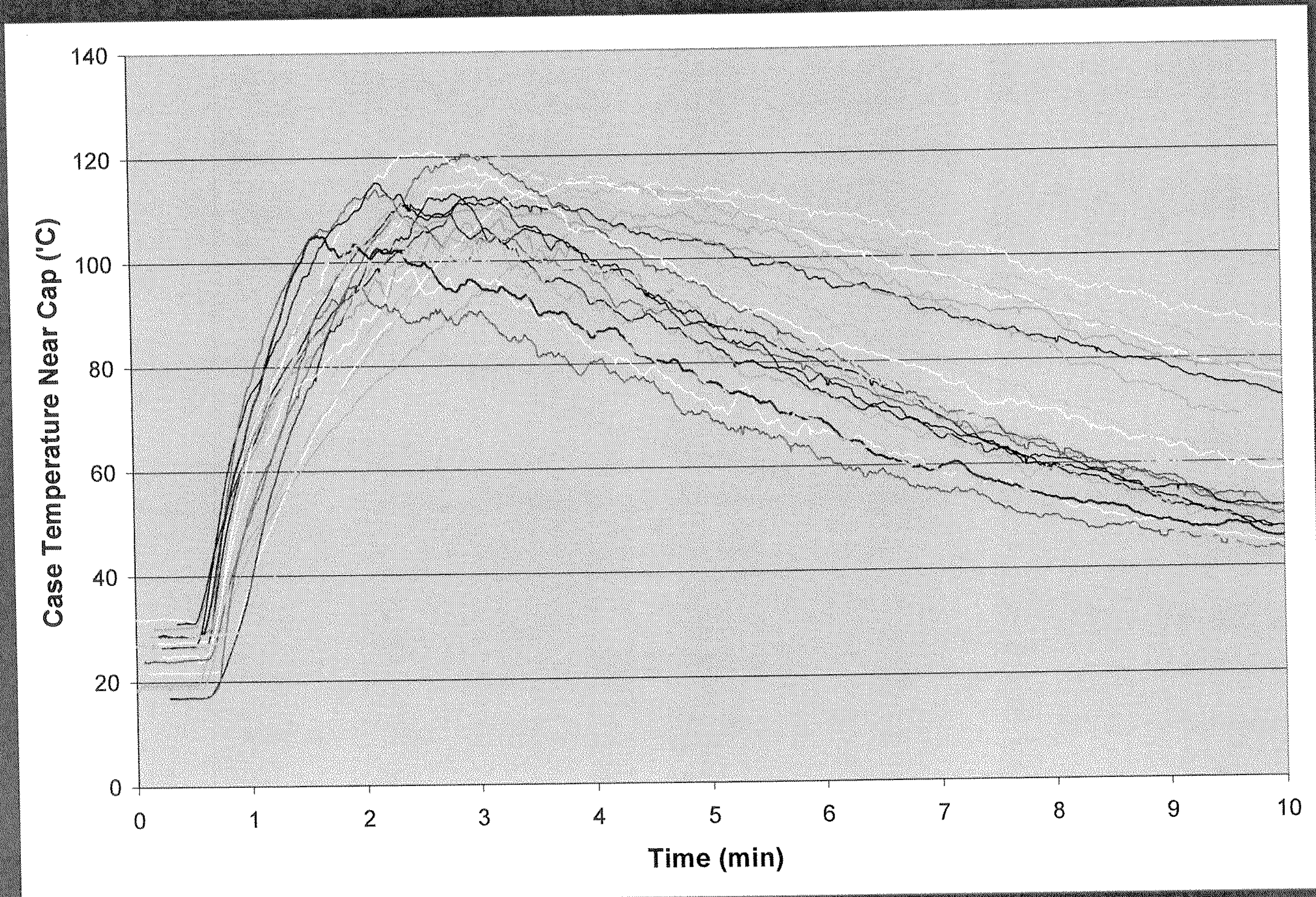


Example 1: 70% SOC, early stage (left), peak heating (right)



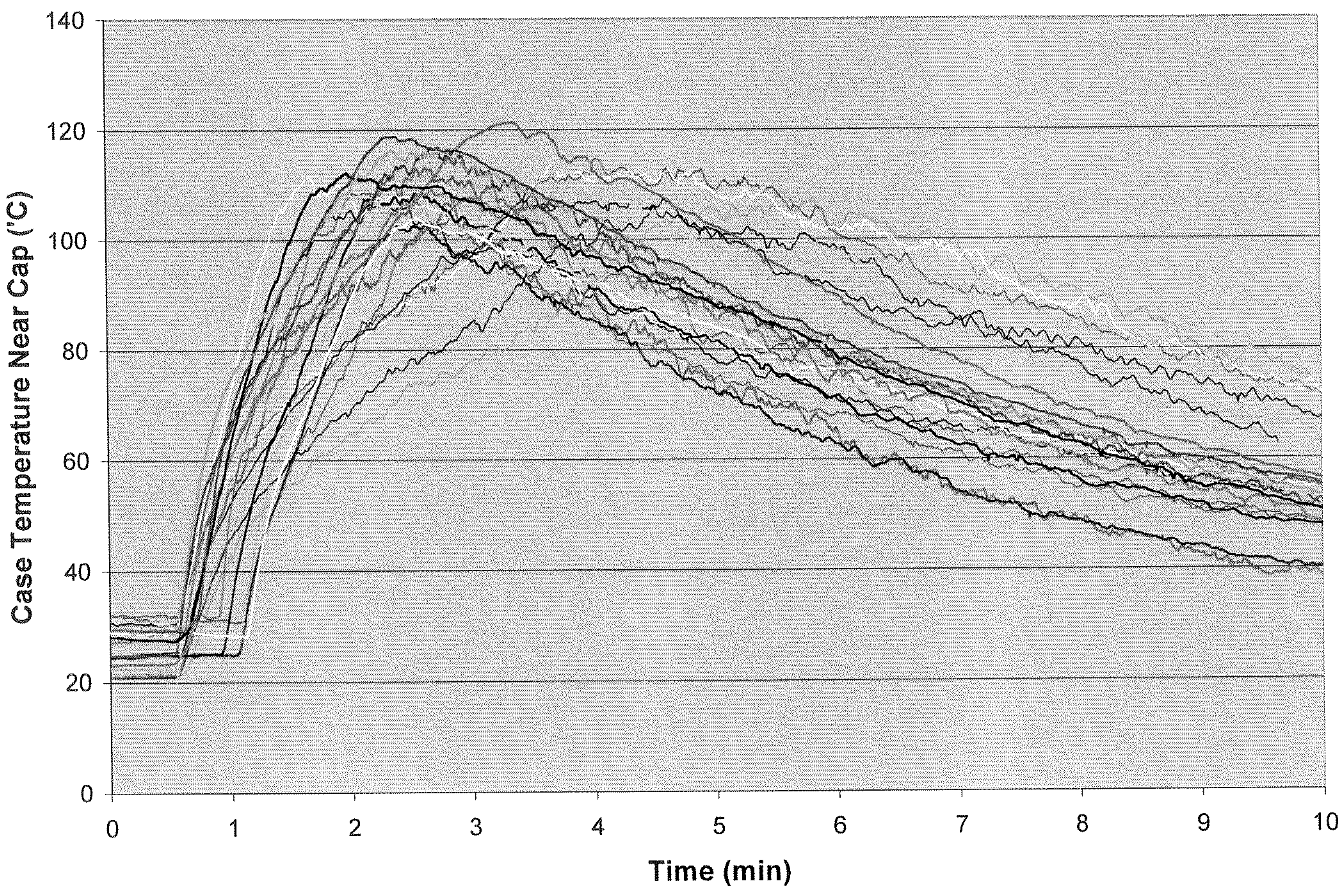
Example 2: 40% SOC, early stage (left), peak heating (right)

Internal Short Outcome



50% SOC Thermocouple Data

Internal Short Outcome



40% SOC Thermocouple Data

Raw Data in Order of Testing

Fire				XXX (3) XXXXX (5) **XXXX (4)**		*xxxxxx (6)* *xxxx (4)*
Energetic Disassembly				XXXX (4) *xx (2)* **X (1)**		*x (1)*
Case Rupture		**X (1)**		**XXX(3)**		
Internal Short	XXXXXXXXX (9) XXXXXCC (7) *xxxx (4)* **XXCXXCXXCX (10)**	XXXXXCXXX (9) XXCXXXCX (8) *xxx (3)* **CXXXXXXX (8)**		X (1) CCCC (4) *x (1)* **C (1)**		*xxc (3)*
High impedance internal short **Temperature Rise < 70 C**	*xc (2)*	*cxxxxx (6)*		*cxxcxx (6)*		*cxxc (4)*
SOC	**40%**	**50%**		**70%**		**100%**

'X' denotes individual crush test w/o case crack

'C' denotes individual crush test with case crack

Bold face denotes refined crush method

Italic/lower case denote preliminary crush method

Refined Data

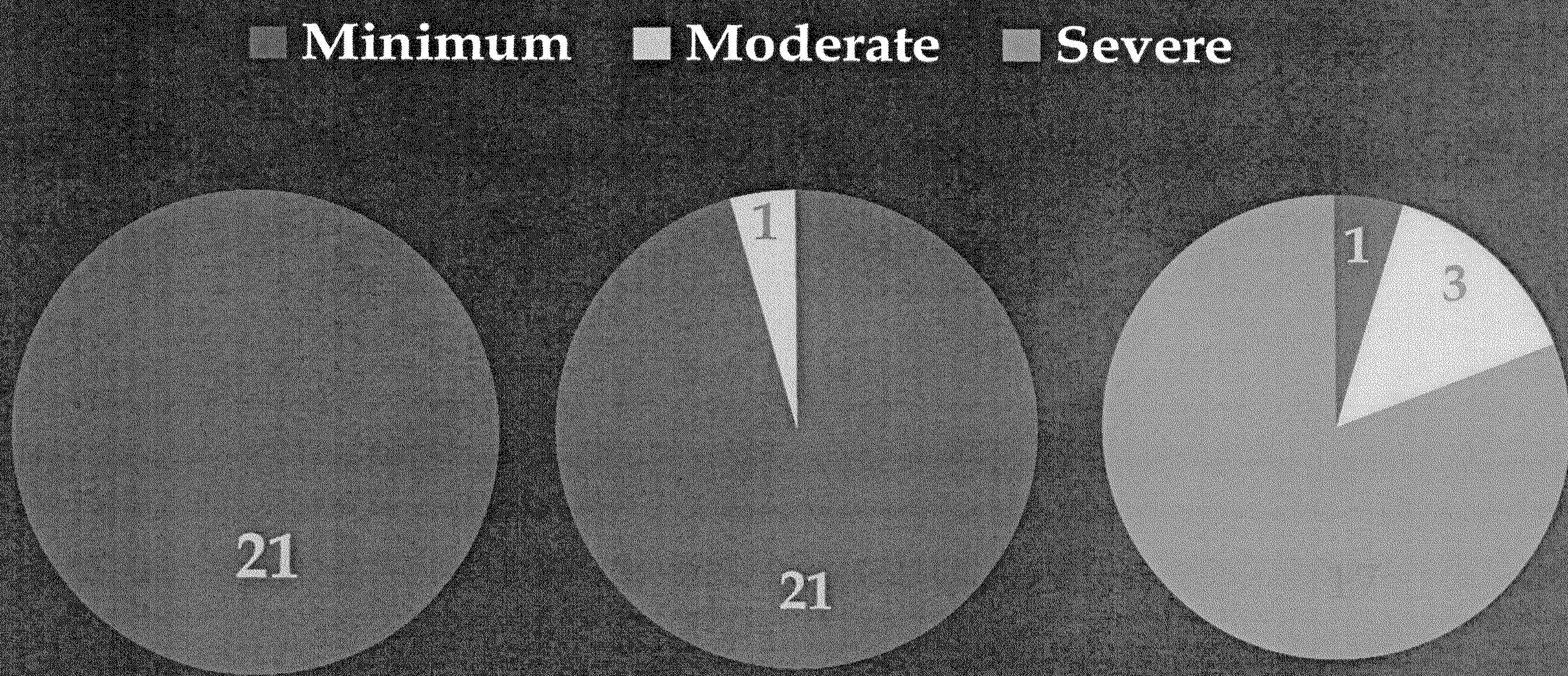
- Set aside results of tests that do not meet criteria for a low impedance internal short or where the case cracked by the mechanical crushing and not from internal pressure

Fire			XXX (3) XXXXX (5) XXXX (4)
Energetic Disassembly			XXXX (4) X (1)
Case Rupture		X (1)	XXX(3)
Internal Short	XXXXXXXXX (9) XXXXX (5) XXXXXXX (7)	XXXXXXXX (8) XXXXXX (6) XXXXXXX (7)	X (1)
SOC	40%	50%	70%

Discussion of Crush Results

- At 100% SOC, a refined crush would typically produce a severe outcome using a refined test method.
- At 70% SOC, a refined crush resulted in severe outcomes for a majority of tests for each brand.
- At 50% SOC, all tests but one resulted in a minimum outcome. The one test resulted in a moderate outcome (case rupture).
- At 40% SOC, all of the tests resulted in a minimum outcome.

Crush Outcome Trends



40% SOC
21 Refined Tests

50% SOC
22 Refined Tests

70% SOC
21 Refined Tests

Preliminary Conclusions

- The refined crush profile method was found to accommodate differences in "cell design" between manufacturers.
- The severity of crush outcome is strongly affected by state of charge. No severe or moderate outcomes were observed during any test of a cell with 40% SOC.
- The severity of crush outcome was not significantly affected by which company manufactured the cell.